

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE January 15, 2000	3. REPORT TYPE AND DATES COVERED Final Jan 1 1994 - May 31 1999	
4. TITLE AND SUBTITLE Hybrid Models for Sequential Decision Making			5. FUNDING NUMBERS G N00014-95-1-0440	
6. AUTHOR(S) Ron Sun				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Missouri-Columbia 201 Engineering Building West Columbia, MO 65211			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research, Code 1141SB 800 N. Quincy Street Arlington, VA 22217			10. SPONSORING/MONITORING AGENCY REPORT NUMBER Not applicable	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) To study hybrid architectures of complex learning, especially as applied to a simulated minefield navigation task, we developed a hybrid connectionist model CLARION as a demonstration of the approach of bottom-up skill learning (from procedural to declarative knowledge). The model essentially consisted of two levels for capturing both procedural and declarative knowledge and enabling bottom-up learning, which differed markedly from existing models. Our Computational and psychological experiments during the past five years demonstrated matches of the model with human data in several domains.				
14. SUBJECT TERMS hybrid models, machine learning, human learning, skill learning			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT unclassified	20. LIMITATION OF ABSTRACT SAR	

FINAL REPORT

GRANT #: N00014-95-1-0440

PRINCIPLE INVESTIGATOR: Ron Sun

INSTITUTION: University of Missouri-Columbia

GRANT TITLE: Hybrid models for sequential decision making

AWARD PERIOD: January 1, 1995 – May 31, 1999

OBJECTIVE: To investigate hybrid architectures of complex learning, especially as applied to a simulated minefield navigation task.

APPROACH: Both human experiments and model developments were undertaken. Model developments were informed by human data, which in turn helped to design further human experiments.

ACCOMPLISHMENTS: We developed a hybrid connectionist model CLARION as a demonstration of the approach of bottom-up skill learning (from procedural to declarative knowledge). The model essentially consisted of two levels for capturing both procedural and declarative knowledge and enabling bottom-up learning, which differed markedly from existing models. Our experiments during the past five years demonstrated matches of the model with human data in several domains. Our focus has been on the minefield navigation (MN) task. A number of other skill learning tasks have also been chosen to be simulated that span the spectrum ranging from simple reactive skills to more complex cognitive skills. The tasks include serial reaction time (SRT) tasks, dynamic control (DC) tasks, the Tower of Hanoi (TOH) task. A good fit was found between the model and the human data, although the work is not yet complete.

In addition, several different ways of incorporating symbolic structures to enhance reinforcement learning are developed in some detail. Different from existing work using symbolic structures in RL, we focus on autonomous learning from scratch without requiring a priori domain-specific knowledge. Thus the role of symbolic methods lies truly in enhancing learning, not in providing a priori domain-specific knowledge to alleviate the need for learning. The key advantage of our methods is that they are more autonomous, more generic, and less expensive to apply, compared with existing methods that rely more on a priori knowledge. Some of our methods generate explicit, symbolic knowledge that are more suitable for comprehension, explanation, and communication of resulting knowledge. Several different domains and their variations have been tackled by our methods.

CONCLUSIONS: A new theoretical framework has emerged that suggests a new way of understanding skill learning — bottom-up learning that goes from procedural to declarative knowledge. There is still much work that needs to be done. Such work include: further development of techniques of autonomous learning, further development of cognitive models and verifications of such models by investigating their fit with new cognitive data in new cognitive domains, and related experimental and theoretical work. Such work can lead to significant advances in several areas.

SIGNIFICANCE: The model we developed suggests the possibility of alternative ways of skill learning different from existing accounts, and highlights an approach that has been

20000210 083

largely neglected. Comparisons with existing learning models (in AI and psychology) showed that our approach as embodied in CLARION has some unique characteristics that other approaches or models did not capture, most notably the bottom-up development and continuous interaction of both declarative and procedural knowledge (different from top-down declarative-to-procedural learning, and beyond separate, parallel learning of the two types of knowledge). The match with human data across various conditions/manipulations is significant, in that it provides evidence with regard to the cognitive validity of the model as well as providing new ideas for further research.

PUBLICATIONS:

(journal papers)

- R. Sun, Learning, action, and consciousness: a hybrid approach towards modeling consciousness. *Neural Networks*, Vol.10, No.7, pp.1317-1331 (the special issue on consciousness, edited by John Taylor). 1997.
- R. Sun and T. Peterson, Some experiments with a hybrid model for learning sequential decision making. *Information Sciences*. Vol.111, pp.83-107. 1998.
- R. Sun and T. Peterson, Autonomous learning of sequential tasks: experiments and analyses. *IEEE Transactions on Neural Networks*, Vol.9, No.6, pp.1217-1234. November, 1998.
- R. Sun, Accounting for the computational basis of consciousness: A connectionist approach. *Consciousness and Cognition*, December, 1999.
- R. Sun and T. Peterson, Multi-agent reinforcement learning: weighting and partitioning. *Neural Networks*, Vol.12, No.4-5. pp.127-153. 1999.
- R. Sun, T. Peterson, and E. Merrill, A hybrid architecture for situated learning of reactive sequential decision making. *Applied Intelligence*, Vol.11, pp.109-127. 1999.
- L. Giles, R. Sun, and J. Zurada, (1998). Neural networks and hybrid intelligent models (an editorial). *IEEE Transactions on Neural Networks*.
- A. Browne and R. Sun, Connectionist variable binding. *Expert Systems: The International Journal of Knowledge Engineering and Neural Networks*, in press, 1999.
- R. Sun, Symbol grounding: a new look at an old idea. *Philosophical Psychology*, in press. 1999.
- R. Sun, Computational models of consciousness: an evaluation. *Journal of Intelligent Systems*, the special issue on consciousness. Vol.9, Nos.5-6. 1999.
- R. Sun, E. Merrill, and T. Peterson, From implicit skills to explicit knowledge: a bottom-up model of skill learning. *Cognitive Science*, in press.

(books and book chapters)

- S. Wermter and R. Sun, (eds.) *Hybrid Connectionist Symbolic Integration*. Lecture Notes in Artificial Intelligence, Springer-Verlag, Berlin. 1999.
- R. Sun, Artificial intelligence. In: W. Bechtel and G. Graham, (eds.) *A Companion to Cognitive Science*. pp.341-351. Blackwell Publishers, Cambridge, UK. 1998.

R. Sun, E. Merrill, and T. Peterson, Knowledge acquisition via bottom-up skill learning. In: C. Leondes, (ed.) *Knowledge Engineering: Systems, Techniques and Applications*. Academic Press, San Diego, CA. 1999.

R. Sun, Supplementing neural reinforcement learning with symbolic methods. In: S. Wermter and R. Sun, (eds.) *Hybrid Connectionist Symbolic Integration*. Lecture Notes in Artificial Intelligence, Springer-Verlag, Berlin. 1999.

S. Wermter and R. Sun, Introduction. In: S. Wermter and R. Sun, (eds.) *Hybrid Connectionist Symbolic Integration*. Lecture Notes in Artificial Intelligence, Springer-Verlag, Berlin. 1999.

R. Sun, An overview of the Clarion project, In: G. Kraetzschmar and G. Palm, (eds.) *Hybrid Information Processing in Adaptive Autonomous Vehicles*. Springer-Verlag, Berlin, Germany. Lecture Notes in Artificial Intelligence, Volume 1624. 1999.

R. Sun and T. Peterson, A subsymbolic+symbolic model for learning sequential decision tasks. In: T. Furuhashi, S. Tano, and H. Jacobsen, (eds.) *Deep Fusion of Computational and Symbolic Processing*. Physica-Verlag (the book series on "Studies in Fuzziness and Soft Computing"), Berlin, Germany. 1999.

R. Sun, Artificial intelligence: connectionist and symbolic approaches. In: N. Smelser and P. Baltes, (eds.) *International Encyclopedia of the Social and Behavioral Sciences*. Pergamon/Elsevier, Kidlington, UK. 2001.

(conference papers)

R. Sun, T. Peterson, and E. Merrill, Bottom-up skill learning in reactive sequential decision tasks. *Proc. of 18th Cognitive Science Society Conference*, pp.684-690. Lawrence Erlbaum Associates, Hillsdale, NJ. 1996.

R. Sun and T. Peterson, Learning reactive sequential decision tasks: the CLARION model. *Proceedings of International Conference on Neural Networks (ICNN'96)*, pp.70-75 and pp.1073-1078. Washington, DC. IEEE Press, Piscataway, NJ. 1996.

R. Sun and T. Peterson, A hybrid model for learning sequential decision making. *Proc. of Joint Conference on Information Sciences*. Vol.1, pp.147-152. Research Triangle Park, NC. Duke University Press, NC. March, 1997.

R. Sun, An agent architecture for on-line learning of procedural and declarative knowledge. *Proc of ICONIP'97*, Dunedin, New Zealand. pp.766-769, Springer-Verlag. 1997.

R. Sun and T. Peterson, A subsymbolic+symbolic model for learning sequential navigation. *From Animals to Animats 5: Proc. of the Fifth International Conference of Simulation of Adaptive Behavior (SAB'98)*. Zurich, Switzerland. eds. R. Pfeifer, B. Blumberg, J. Meyer, and S. Wilson. pp.246-251. MIT Press, Cambridge, MA. 1998.

R. Sun, E. Merrill, and T. Peterson, A bottom-up model of skill learning. *Proc. of 20th Cognitive Science Society Conference*, pp.1037-1042. Lawrence Erlbaum Associates, Mahwah, NJ. 1998.

R. Sun, E. Merrill, and T. Peterson, Skill learning using a bottom-up hybrid model. *Proc. of The Second European Conference on Cognitive Modeling*, Nottingham, UK. pp.23-29. Nottingham University Press. April, 1998.

- R. Sun and C. Sessions, Learning to plan probabilistically from neural networks. *Proceedings of IEEE International Joint Conference on Neural Networks*, pp.1-6. Anchorage, Alaska. May 4-9, 1998. IEEE Press, Piscataway, NJ.
- R. Sun and T. Peterson, Hybrid learning incorporating neural and symbolic processes. *Proceedings of IEEE International Conference on Fuzzy Systems*, pp.727-732. Anchorage, Alaska. May 4-9, 1998. IEEE Press, Piscataway, NJ.
- T. Peterson and R. Sun, An RBF network alternative to a hybrid architecture. *Proceedings of IEEE International Joint Conference on Neural Networks*, pp.768-773. Anchorage, Alaska. May 4-9, 1998. IEEE Press, Piscataway, NJ.
- R. Sun and T. Peterson, Automatic partitioning for multi-agent reinforcement learning. *Proc. of International Conference on Neural Information Processing (ICONIP'98)*. Kitakyushu, Japan. pp.268-271. IOS Press, Burke, VA, USA. October, 1998.
- R. Sun and C. Sessions, Extracting plans from reinforcement learners. *Proceedings of the 1998 International Symposium on Intelligent Data Engineering and Learning (IDEAL'98)*. pp.243-248. eds. L. Xu, L. Chan, I. King, and A. Fu. October 14-16, 1998. Springer-Verlag, Heidelberg, Germany.
- R. Sun, Supplementing neural reinforcement learning with symbolic methods: possibilities and challenges. *Proceedings of International Joint Conference on Neural Networks*, Washington, DC. July 10-15, 1999. IEEE Press, Piscataway, NJ.
- R. Sun, Knowledge extraction from reinforcement learning. *Proceedings of International Joint Conference on Neural Networks*, Washington, DC. July 10-15, 1999. IEEE Press, Piscataway, NJ.
- R. Sun and T. Peterson, Partitioning in reinforcement learning. *Proceedings of International Joint Conference on Neural Networks*, Washington, DC. July 10-15, 1999. IEEE Press, Piscataway, NJ.
- R. Sun and C. Sessions, Self segmentation of sequences. *Proceedings of International Joint Conference on Neural Networks*, Washington, DC. July 10-15, 1999. IEEE Press, Piscataway, NJ.
- R. Sun and C. Sessions, Bidding in reinforcement learning, a paradigm for multi-agent systems. In: O. Etzioni, J. Muller, and J. Bradshaw, (eds.) *Proc. of The Third International Conference on Autonomous Agents (AGENTS'99)*, pp.344-345. Seattle, WA. ACM Press, New York. May 1-5, 1999.
- R. Sun and C. Sessions, Reinforcement learning with bidding for automatic segmentation. *Intelligent Agent Technology: Systems, Methodologies, and Tools — Proceedings of the First Asian-Pacific Conference on Intelligent Agent Technology*, Hong Kong. (eds.) J. Liu and N. Zhong. World Scientific, Singapore. pp.84-93. December, 1999.

AD NUMBER		DATE	DTIC ACCESSION NOTICE
1. REPORT IDENTIFYING INFORMATION			REQUESTER: 1. Put your mailing address on reverse of form. 2. Complete items 1 and 2 3. Attach form to reports mailed to DTIC. 4. Use unclassified information only 5. Do not order document for 6 to 8 weeks. DTIC: 1. Assign AD Number. 2. Return to requester
A. ORIGINATING AGENCY Office of Naval Research			
B. REPORT TITLE AND/OR NUMBER Hybrid models for Sequential Decision making			
C. MONITOR REPORT NUMBER			
D. PREPARED UNDER CONTRACT NUMBER N00014-95-1-0440			
2. DISTRIBUTION STATEMENT unlimited			

DTIC Form 50
JUL 96

PREVIOUS EDITIONS ARE OBSOLETE